Designing Environments

Alessandra Battisti
Serena Baiani *Editors*

ETHICS: Endorse Technologies for Heritage Innovation

Cross-disciplinary Strategies

Springer

Designing Environments

Series Editors
Michael U. Hensel, Head of Department of Digital Architecture and Planning, Vienna University of Technology, Vienna, Austria
Claudia R. Binder, Dean of EPFL ENAC, École polytechnique fédérale de Lausanne, Lausanne, Vaud, Switzerland
Defne Sunguroğlu Hensel, Associate Professor, Landscape Architecture and Urban Ecology, Southeast University, Nanjing, Jiangsu, China

This series seeks to address the unfolding climate, environmental and ecological crisis from a broad interdisciplinary perspective and in relation to the impact of human transformations of the environment. The aim is to shift away from segregated modifications of the environment divided into domains and scales, systems and objects, with at best minimum negative impact for the environment, towards an integrative interdisciplinary approach that understands, models and modifies the environment in comprehensive and integrative manner and with net positive impact on the environment. This endeavour involves earth, environmental and life sciences, environmental informatics, computer science, and the disciplines that centrally concern the transformation of the terrestrial environments, such as architecture, landscape architecture and urban design, as well as agriculture and food production. From a methodological perspective, computer and data science play a role in facilitating multi-domain and multi-scale models of environments with the purpose of both analysis and design. At the same time, the series will place the discussion in a necessary cultural context and also discuss the need for ethics in which an alternative approach to the transformation of the environment needs to be based on.

The Series Editors welcome book proposals on the following topics: paradigms, theory and methods for integrative inter- and transdisciplinary approaches to understanding, modelling and modifying environments; relevant historical and contemporary case studies; relevant current research projects; related data science and computer science approaches.

Alessandra Battisti • Serena Baiani
Editors

ETHICS: Endorse Technologies for Heritage Innovation

Cross-disciplinary Strategies

Springer

Editors
Alessandra Battisti
Department of Planning, Design and Technology, Faculty of Architecture
Sapienza University of Rome
Rome, Italy

Serena Baiani
Department of Planning, Design and Technology, Faculty of Architecture
Sapienza University of Rome
Rome, Italy

ISSN 2730-6526 ISSN 2730-6534 (electronic)
Designing Environments
ISBN 978-3-031-50120-3 ISBN 978-3-031-50121-0 (eBook)
https://doi.org/10.1007/978-3-031-50121-0

This Springer imprint is published by the registered company Springer Nature Switzerland AG
The registered company address is: Gewerbestrasse 11, 6330 Cham, Switzerland

Paper in this product is recyclable.

Contents

Chapter 10
Design and Installation of Superlight Construction Systems for the Sun Protection of Cultural Heritage: Ongoing Research and Field Tests in Milan and Pompeii

Alessandra Zanelli, Carol Monticelli, Salvatore Viscuso, and Christian Renan Endara Vargas

Abstract The chapter presents two experimental research tasks conducted by a multidisciplinary group of scholars of restoration, architectural composition, technical physics, and technical architecture and coordinated by architectural technology researchers. We intend to present the entire workflow – multi-criteria analysis, acquisition of experimental data, design, prototyping, installation, and monitoring – inherent to two different environmental protection devices of museum spaces. The first case study (Castello Sforzesco) concerns the creation of protective screens applied to the windows of the Sala delle Asse and optimized for the correct conservation of Leonardo da Vinci's monochrome preserved there. The second case study (Pompeii) concerns the design of a ventilated textile roof for the protection of the mosaics and frescoes of the House of Orion. Through the two case studies, the authors intend to present an innovative intervention methodology to ensure the usability and conservation of the heritage, through the design of ultra-lightweight, durable and reversible construction systems, free of metal parts and capable of fully exploiting the optical-visual, thermo-hygrometric and mechanical properties of technical textiles and ultra-lightweight tensile membrane systems.

A. Zanelli (✉)
Department of Architecture, Built Environment and Construction Engineering (ABC), Politecnico di Milano, Milan, Italy
e-mail: alessandra.zanelli@polimi.it

C. Monticelli · S. Viscuso
Department of ABC, Politecnico di Milano, Milan, Italy

C. R. E. Vargas
School of Architecture, Urban Studies and Construction Engineering, Politecnico di Milano, Milan, Italy

A. Battisti, S. Baiani (eds.), *ETHICS: Endorse Technologies for Heritage Innovation*, Designing Environments,
https://doi.org/10.1007/978-3-031-50121-0_10

Keywords Technical textiles · Knitted textiles · Bending-active structures · Tensegrity structures · Sun protection · Fire protection · Reversible building systems

10.1 Introduction

Nowadays, guidelines for the preservation of cultural assets have taken the innovative step of outlining the need for a value-led approach that keeps protection and management together, starting from shared, common long-term strategic plans, with the final aim to enhance the reciprocal benefits for heritage and society. Nevertheless, protecting and refurbishing a cultural heritage asset are often conflicting goals (Demas 2013; UNESCO 2013), due to the fact that new materials and components useful to provide a comfortable area for visitors and/or to create new enclosures in an ancient open-air environment shall compromise the long-term preservation of the cultural asset itself.

Innovative approaches in protection, conservation, presentation and rehabilitation should be linked to the use of innovative textiles, while lightweight structures could be useful when a precautionary principle seems preferable (Rosina et al. 2011; Zanelli 2015). Ultra-lightweight, soft materials – as technical textiles – shall provide at least a short-term preservation, while temporary structures and reversible construction methods shall minimize the impact on the asset being protected, every time there is a lack of long-term, scientifically based plans, widely accepted by all the bodies in charge of the heritage conservation.

This chapter shows two cases studies where the institution in charge for the preservation and the valorisation of the heritage assets are willing to adopt an intervention approach that leaves the door open for future generations to revise how the asset is conserved.

The two cases are quite different from each other, due to the requirements and needs of the administrations of the respective cultural assets. Nevertheless, they share the following priority requirements: (1) sun protection, (2) fire protection; and (3) the simplified installation method, minimally invasive towards the existing masonry, based on dry and reversible techniques.

In both cases, the role of the technological design emerges as key discipline, able to lead the whole multi-disciplinary experimental design-to-construction path, starting from the selection, the characterization and/or the simulation of the appropriate soft and lightweight materials, till the definition of the reversible installation procedures of the protection system.

Some conflicting requirements were considered during the multidisciplinary research, and their impact was evaluated, thanks to multi-criteria analysis. After the optimization and installation phases, the monitoring campaigns are still ongoing.

10.2 From the Material Properties to the Design

In the last few decades, rapid developments in material production types and surface refinement of membrane materials (e.g., coatings), along with advanced CFD and other computer simulation methods, have been constant stimuli for innovation. As a result, modern membrane technology is a key factor for intelligent, flexible protective skin, complementing and enriching today's range of traditional building materials. The development of functional coatings on membrane material has a special impact for the improvement in terms of durability, thermal and acoustical properties, low-emissivity and fire resistance, such as the development of low-E-coated technical textiles with an emissivity rate less than 40% (Cremers 2009; Zanelli et al. 2023).

When the membrane structure is intended as protective system of public spaces, as well as cultural heritage assets, fire-proofing is one of crucial expected performances, even if it often limits the wider range of textiles and polymeric coatings available for structural membranes.

Referring to the fire safety regulation, any fireproof treatment for architectural applications certainly represents a process that covers a lack of performance of the initial raw materials, thus obtaining high-performative products also for public uses. In case of textile applications, anti-flame means fire-retardant: as happens for other families of building products, the regulatory standards describe a gradual performance, in relation to the behaviour of the fabric subjected to the flame before its complete combustion, to the release of fumes, dripping or the release of incandescent fragments.

To make a fabric flame retardant or even anti-flame, the industry can proceed in two ways: using fire retardant fibres in their molecular structure and which make the fabric intrinsically flame retardant or applying fire retardant treatments on traditional fabrics which, after the weaving, are post-treated with products capable of promoting carbonation in contact with fire, guaranteeing sufficient time for the flame-retardant effect, even in the face of wear and tear of the fabrics over time (Zanelli 2009).

The following sections describe two different case studies of innovative textile products able to perform an qualified level of fire protection, thermal and environmental performances, for indoor and outdoor applications.

10.3 Case Study 1: Milan, Castello Sforzesco, 2019

The first case study shows the design-to-construction process of an innovative ultra-lightweight building system applied in June 2019 to a pair of windows of Castello Sforzesco, Milan, Italy. A multi-disciplinary team of researchers experimented an innovative and accurate workflow, where preliminary measures and parallel testing campaigns on unusual textile materials were supporting the design phases, the material choices as well as the structural concept of the new developed window screens.

The main novelty of the two bespoke screens is that they have to mitigate the indoor hygroscopic and thermal conditions of the room “Sala delle Asse” at Castello Sforzesco, thus contributing to the right preservation of the Leonardo Da Vinci frescoes, one of the most important artifacts of cultural heritage in Milan. Given the need to avoid perforation on that historically relevant context, the project of innovative tensile membrane screens was facing several conflicting challenges, and the final design was the result of a multidisciplinary designing-while-testing process led by the Architecture, Built Environment and Construction Engineering Department’s Labs at Politecnico di Milano, Milan, Italy (Zanelli 2015; Zanelli et al. 2020). The main challenges were (1) the integration of full screens able to be easily installed and thought as reversible additions to historical buildings; (2) to experiment a kind of enhancement of the visual perception through the new screens, so that the outdoor courtyards will be perceived by visitors inside the museum’s rooms; this requirements might be conflicting with the need of increasing the thermal comfort of the rooms as well as the solar protection of the frescoes inside the room; and (3) then the creation of research-based design methodology for the application of novel screens in several cultural heritage contexts; everywhere the preservation of the heritage assets has to be balanced with the preservation and valorization of the historical building that contains those assets.

Six months of preliminary testing campaign was conducted before the design process, to support the innovative design and installation method of the screens. The first novelty is that the screens are self-standing tensile membranes supported by ultra-lightweight frames. The latter innovative aspect is that the screens are knitted and fire-proof textiles made of non-flammable thread Trevira®. A further special requirement of the knitted membrane is that it needs to prevent the direct sunlight inside the room, as well as to decrease the humid air flows passing through the old windows frames, as they may cause further damages to the ancient walls and their frescoes. The design team was able to control the deformability of the knitted fabrics, by testing several fabrics, with the final aim to control the elasticity of the knitted fabric and to let it to accomplish the right level of each expected performance. Eventually, a textile hybrid structure was developed (Kolo 2018) as (1) a bending-active and form-active building system, due to its self-standing principle that would not require drilling on the vault; (2) an unconventional and fire-resistant knitted textile materials; and (3) a flexible systems that needs to be characterized both in terms of mechanical and thermal-optical performances, both during its stretching (the service life) and when it is relaxed (during the installation and maintenance procedures).

The interaction between the different expertise involved in the design process and in the experimental measurements is shown in the diagram of Fig. 10.1. The testing campaign was starting from the early-stage design process and was constantly refining the novel building product.

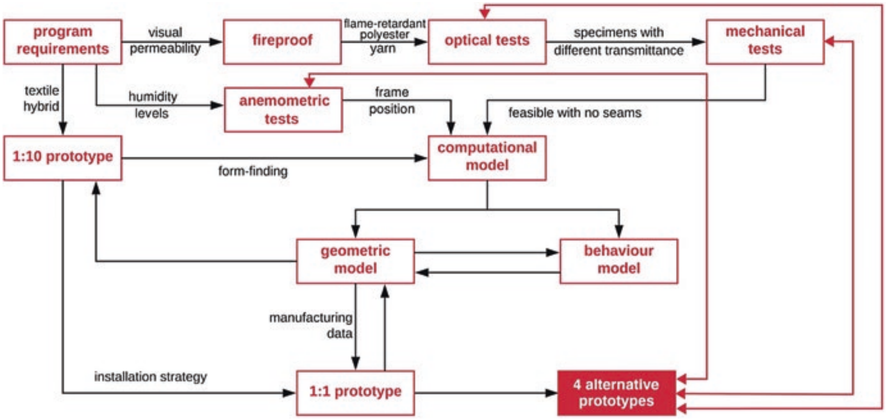

Fig. 10.1 A flow chart of the various competences involved in the project, showing the feedback loop of their interaction (Kolo 2018; Zanelli et al. 2020)

A first understanding of the visual and solar transmittance led the further selection of suitable textile materials, able to match also the mechanical requirements and the mandatory need of fire-proofing performance. Actually the choice of the types of knitted fabrics was very limited to the ones using the flame-retardant yarn. Design choices were updated with these test results and were followed by mechanical studies on the stretching properties of the knitted textiles to define the project's feasibility. These data served as an input to the performative computational design phase (Fig. 10.2), which aided the construction of the mock-ups made of glass fibre-reinforced elements that are bending the textile membrane. A first 1:1.5 scale mock-up (Fig. 10.3) was useful to test the bending active principle, while a further 1:1 scale demonstrator was later built up on the producer's warehouse, supporting the development of the removable kit of the whole tensile screen, as well as looking for the final optimization loop of detailed design. A final step of verification would be the installation in situ, not really in the room with Leonardo's frescoes (Sala delle Asse) but in the adjacent room (Sala del Gonfalone), characterized by the same solar orientation. That precautional decision was justified by the need to prevent any possible damage to the frescoes, having the time to lead a wider experimental campaign on the innovative tensile membrane screens applied to the ancient castle's windows. Two different alternative prototypes, with different densities of the textile, were installed on site.

These 3-m-wide, different dense, textile screens are still on site (Fig. 10.4), and the monitoring campaign is still ongoing, with the aim to assess and validate the application of knitted fabrics in other cultural heritage sites.

The innovative use of knitted fabrics integrated into tensile membrane structure and combined with bending active elements (fibreglass-reinforced elastic bars) has been exploiting the vast architectural potential of the knitted fabrics (Ahlquist et al. 2013; Lienhard 2014; Tamke et al. 2016). Knitted-fabrics integrated in

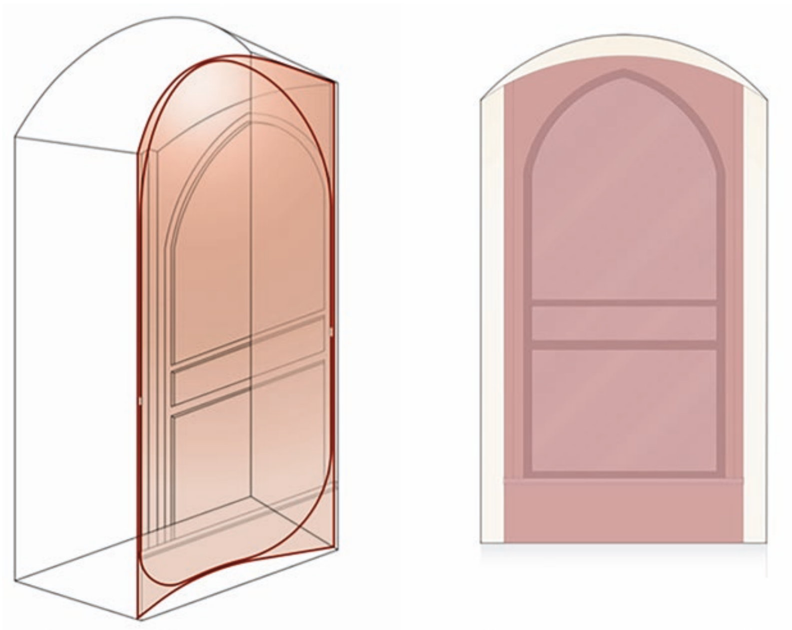

Fig. 10.2 The shape of the bending-active self-standing structure (Kolo 2018)

tensile membranes mainly show the advantage of a wider degree of flexibility during the installation and maintenance, in comparison with the traditionally used coated fabrics.

The pre-selected samples include two different thermo-fixated knitted textiles, Ogliastra and Levanzo (4Spaces © 2017), which have the same knit pattern, also identified as Lacoste loop-and-tuck piquet knit (Fig. 10.5).

In order to overcome the dimensional limits of the current production and without disregarding at the same time the Castello Sforzesco's protection board who was asking to avoid sewn seams in the whole screen panel, the elongation from stretching the fabric needs to be assessed, in both the direction of the fabric. Thus, uniaxial and biaxial stress tests were performed, aiming at studying the elastic deformation of the knitted pre-selected samples. This further study on the mechanical properties of the pre-selected samples allowed the designers to use that crucial information on the behaviour of the membrane during its reversible installation process, in order to facilitate the fixing, the unfixing as well as the cleaning and the repairing of the fabric. The definition of the prestress needed during the assembling stage was a further important aspect to be optimized, in terms of exploiting better the material properties, taking into account that knitted textiles typically highly differ from the current coated-fabrics used in membrane-based building systems (Huang et al. 2000).

Fig. 10.3 A view of the scaled prototype installed at TextilesHUB Laboratory (Zanelli et al. 2020)

Fig. 10.4 The current experimental installation of two screens at Sala del Gonfalone, Castello Sforzesco. The textile panels tested on the two windows are experimenting different degrees of density, air permeability and translucency to the natural light (Zanelli et al. 2020)

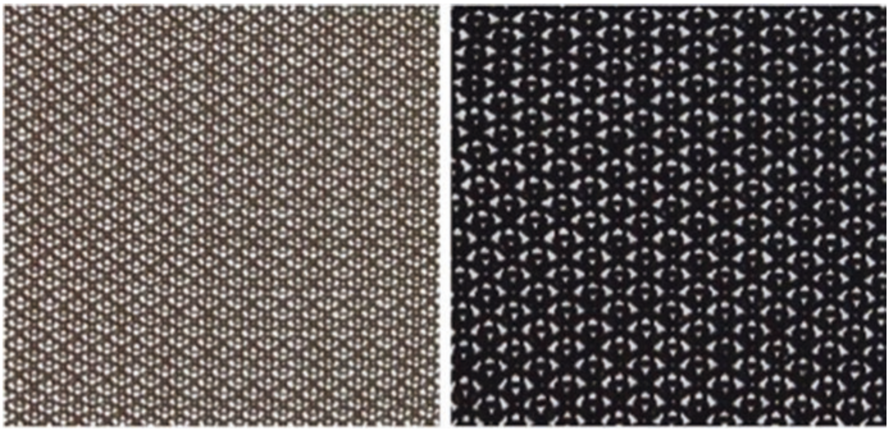

Fig. 10.5 Textures of the pre-selected samples, which were matching the mechanical and optical requirements of the project (4Spaces ©)

The performed uniaxial and biaxial tests assessed that the mechanical behaviour of the pre-selected samples was really compatible with the real use of knitted membrane simulated during the design phase (Monticelli et al. 2022).

Firstly, uniaxial tests were carried out to investigate elongation in weft and in warp direction separately; they were held according to the EN ISO 13934 by first pretensioning and then imposing displacement control in a room of temperature 23 °C.

Later on, specific biaxial loading profiles were based on design and feasibility considerations, starting from the EN 17117:2018 method, which deals with the coated and plain fabrics (Fig. 10.6). In particular, the forces were again limited to the first part of the stress/strain graph, specifically to a 21% strain, because of the behaviour of the knitted fabrics that start to deform in a plastic manner for lower loads than 1/4 of their ultimate tensile strength, as measured during the uniaxial test campaign (Monticelli et al. 2022).

Furthermore, the selected knitted fabrics were retested with the same corresponding load profiles, and one sample was also washed (water temperature 30 °C) to assess the shrinkage of the textile.

Even if the testing procedure was calibrated for the Castello Sforzesco knitted screen, the whole testing-driven design methodology shall be replicable every time a new textile can be proposed in an unusual structural application, in order to provide insight into the real behaviour of the membrane component, during its service life, and when it has to be dismantled and remounted many times.

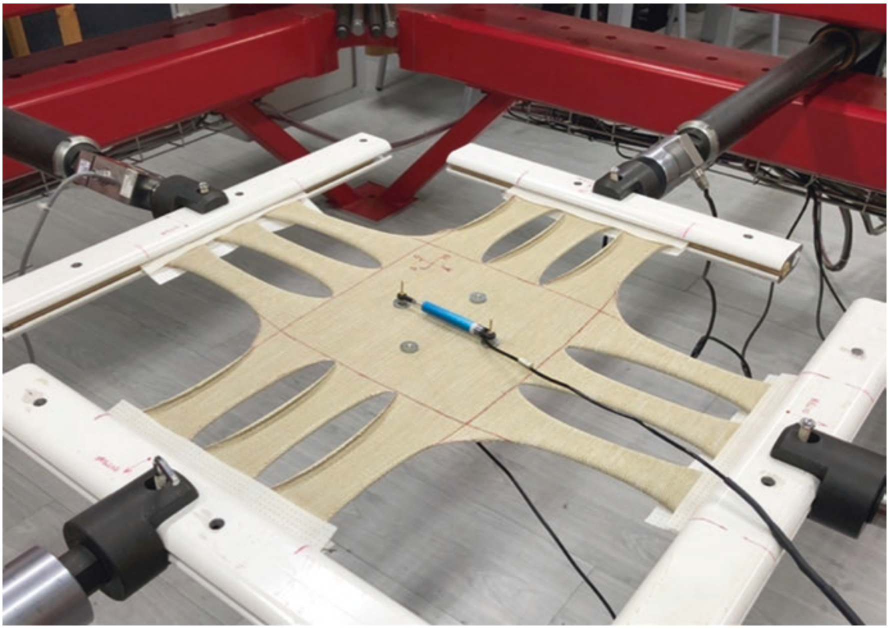

Fig. 10.6 The biaxial testing phase: the sample placed into the profiles and then attached to the motors (TAN group, ABC Dept., Politecnico di Milano)

10.4 Case Study 2: Pompeii, House of Orion, 2022

Within the planned interventions from the Pompeii Superintendence for the conservation and the fruition of the House of Orion, the geometric perception of the atrium will be emphasized through a slight difference in height compared to the other rooms, necessary for the rules of perspective perception. The atrium will not reach the height that it could have, following the Vitruvian rules of proportion, but will allude to an unfinished measure. The latter will be highlighted further by a translucent textile canopy. Not being able, in fact, to respect the canonical height because it would overhang the heights of the finds in the current Pompeian urban context, it was decided to remind to the ancient "tested" roof through its hypothetical figure made with a translucent material, which will illuminate the atrium with diffused light and will highlight the condition of emptiness and continuity towards the outside.

The textile cover will be completely removable and reversible. The fabric and the relative structure are designed during the executive phase with an interdisciplinary collaboration of researchers of Politecnico di Milano (departments DABC and DICA), with the final aim at simulating and foreseeing the ideal environmental conditions for the conservation of the ancient walls and pavements.

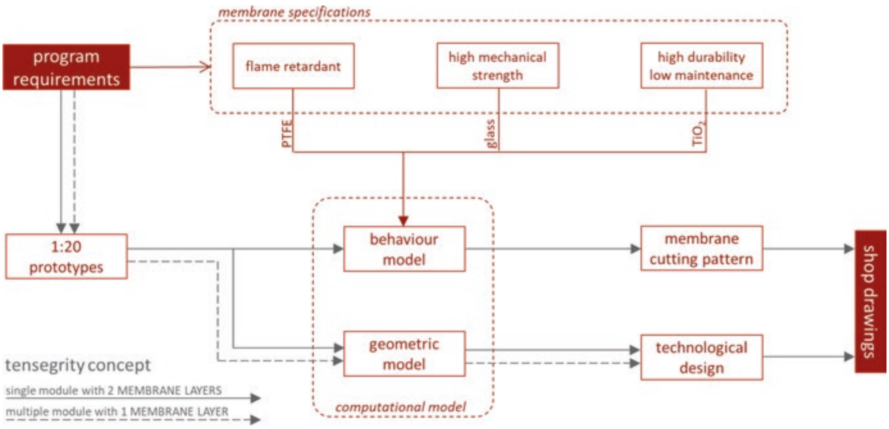

Fig. 10.7 The methodological workflow of case study 2

Due to the historical value, the design team has faced with extremely strict design conditions. A great deal of these special demands can be complied using lightweight tension structures.

The research work (Fig. 10.7) firstly focuses on the concept design of a double-layer tensile canopy, with two or more compressed tubes (flying masts) into the multilayered roof. In fact, the obtained tensegrity system – with compressed elements that strain both membranes – creates an internal cavity that work as a “climate envelope.” In fact, the buffer zone between the two membrane layers permits:

– The mechanical-controlled internal ventilation of the roof during the summer season
– A more efficient protection of the ruins against the sun radiation, due to the double UV filtering offered by the doble-layer design
– A proper thermal insulation, using stationary air in the buffer zone, for the winter season
– A better control of the humidity that avoids moistures

The adoption of a double membrane structure permits to reflect the changing luminosity of the sky (through the upper layer) and to transfer it to the inner skin, which spreads a diffused light into the atrium. The structural design alternatives, modelled using parametric software (Rhino Grasshopper), have been studied in parallel trough the fabrication of scaled maquettes made of nylon mesh and tin ropes. This experimental step permits to preliminarily verify the tensile shape (form-finding) of the design alternatives, which differ one to each other for the numbers of tensile modules and compressed bars, as well as the presence or not of a central opened skylight by using at least four compressed bars (Fig. 10.8).

The multiple-module tensegral system recalls the geometric cryptographs found on the floor of the villa and permits to optimize the rotation of each flying mast in

Fig. 10.8 Design alternatives of double-layer tensile canopies

relation to the sun direction (Fig. 10.9); it appears very innovative and high-risk building systems for the peculiarity of the contest, while the single-module proposal creates a geometry that remind to the ancient "tested" roofs (Fig. 10.10).

After the form-finding study of the different design alternatives using scaled models, it is necessary to check the load-bearing capacity through the structural analysis of single-frame tensegrity concept, which is the design alternative that uses a larger span of tensile membrane. This analysis became crucial if we consider that the type of PTFE/glass membrane to adopt for the analysis is a type-I (Knippers et al. 2011), thus extremely thin, translucent and lightweight, in order to do not overload the masonry below the roofing frame to which the fabrics are fixed. The expected structural response of such structures is strongly nonlinear in terms of both the impact of geometry changes and material behaviour: if all the requirements are fulfilled, the structure can be fabricated. To make this step possible, it is necessary to generate cutting patterns as membrane structures exhibit their curvature, and therefore, they must be approximated by a certain number of planar patterns.

The following paragraphs focuses on all those steps:

1. Digital form-finding of tensioned elements (membranes and cables)
2. Structural analysis of tensioned and compressed elements
3. Compensation of tensioned membranes and generation of the cutting pattern for the fabrication
4. Technological design of anchor details

The workflow presents modelling steps created using the RFEM software, including the add-on modules RF-FORM-FINDING and RF-CUTTING-PATTERN for the design and analysis of membrane structures, which were developed recently by the cooperating Czech companies Dlubal Software s.r.o. and FEM Consulting s.r.o.

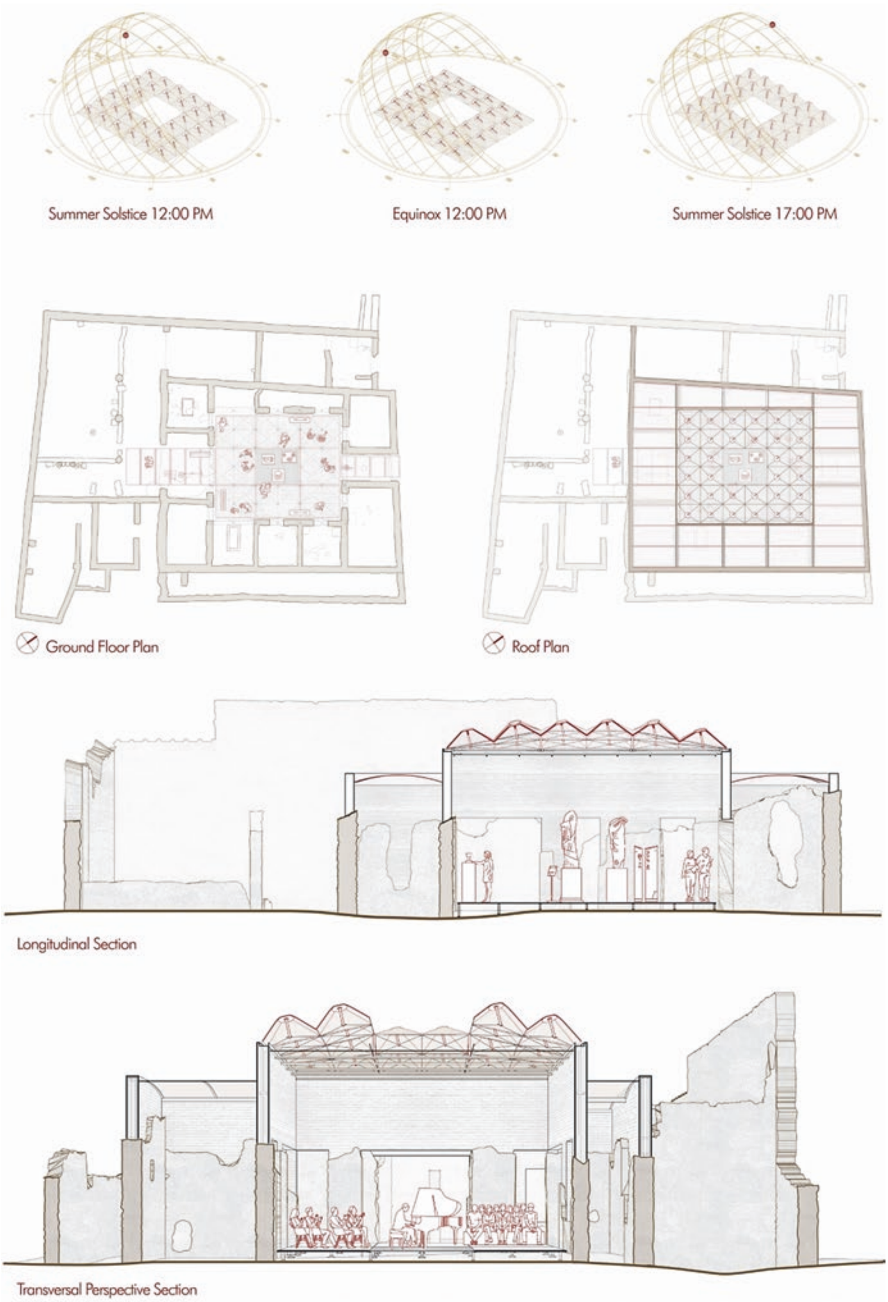

Fig. 10.9 Multiple-module tensegrity concept. (Designed by the author Endara Vargas)

Fig. 10.10 Single-module tensegrity concept (Courtesy of Arch. Luisa Ferro, Politecnico di Milano, Dept. of Architecture, Built environment and Construction Engineering)

10.4.1 Form-Finding

The method of numerical form-finding increased its importance with the fast development of computing power. It is easy and quick to implement the numerical model in a software and change its properties as often as necessary to identify the best shape. Also, there is the possibility of modifying other characteristics, such as the stresses in the membrane, or varying boundary elements to get the optimal result. In short, the now available changes to optimize a structure are the foundation for the modern design process of membrane structures. The subsequently utilized finite element static software Dlubal RFEM uses two different methods, which are both based on the form-finding methods published by K. U. Bletzinger and E. Ramm in 1999: projection method and tension method.

The methods that have been proposed and implemented into software as tools for the form-finding process can be divided into many categories, such as "Force Density Method" (FDM), "Dynamic Relaxation" (DR), "Updated Reference Strategy" (URS), "Natural Force Density Method" (NFDM), etc. (Lienhard and Bletzinger 2010). When calculating the shape of a membrane structure, there is a great difference between the classic FDM and the other methods listed above, since the FDM replaces the membrane by a cable mesh, while the other methods use surface finite elements for the membrane. In addition to this great difference, there are some smaller differences between the methods using 2D FE. Summing up, the main methodological difference is that the form-finding process can be assumed as a static or dynamic task (or even as a specially formulated form-finding task, for more accurate studies).

There is one interesting phenomenon when comparing the shape calculation of a structure or structural parts under tension and under compression. While the structure under tension takes the stable equilibrium position, the structure under compression takes the unstable equilibrium position. As a result of that fact, the tensioned structures converge to the equilibrium position if the required prestress is physically realizable. Therefore, a local stabilization of the parts under the compression has been designed and implemented. For both the above-described static and dynamic methods, the equilibrium state of the structure subjected to the form-finding process can be written in the same manner as the equilibrium state of the body in FE analysis.

The design team proposed a solution that duplicates and reflects on the horizontal plane the tensioned membrane, in order to obtain a reciprocal system that blocks two flying masts. These compressed elements – made of anodized aluminium tubes – are also supported by a steel cable system that is interlocked with the four corners of the roof. By setting the length of the tube on 1.20 m, it figures out a roof slope of 5%, according to the need of an efficient pretension of the membranes and the reduction of the security coefficient for the snow load analysis. The example of such a structure, which solves the phenomenon described above, is shown in Fig. 10.11.

10.4.2 Structural Analysis

Due to the unusual tensile shape that has to be reached, the structural analysis of the designed canopy for the House of Orion in Pompeii exhibits significant nonlinearities. These are caused by both the geometrical changes of the structure during its loading and the nonproportional changes of the internal forces depending on the strains of material because it is necessary to consider at least zero compression resistance on the whole membrane surface.

For the structure, five load cases are considered: self-weight, three different wind loads, and the snow load. For the wind load, the maximal dynamic pressure is calculated according to the Cp values that are published on the Appendix A1 of European Design Guide (Forster and Mollaert 2004). The characteristic value of the snow load is *Sk = 0.60 kN/sm*. The buffer of the cavity (min 30 -max 120 cm) obligates to duplicate the reactions for both membranes.

For the consequent structural analysis, the combination expressions for Ultimate Limit State (ULS) and Serviceability Limit State (SLS) are used, according to EN 1993-1-1:2005. The results of one the Ultimate Limit State combinations are shown as an example in Fig. 10.12.

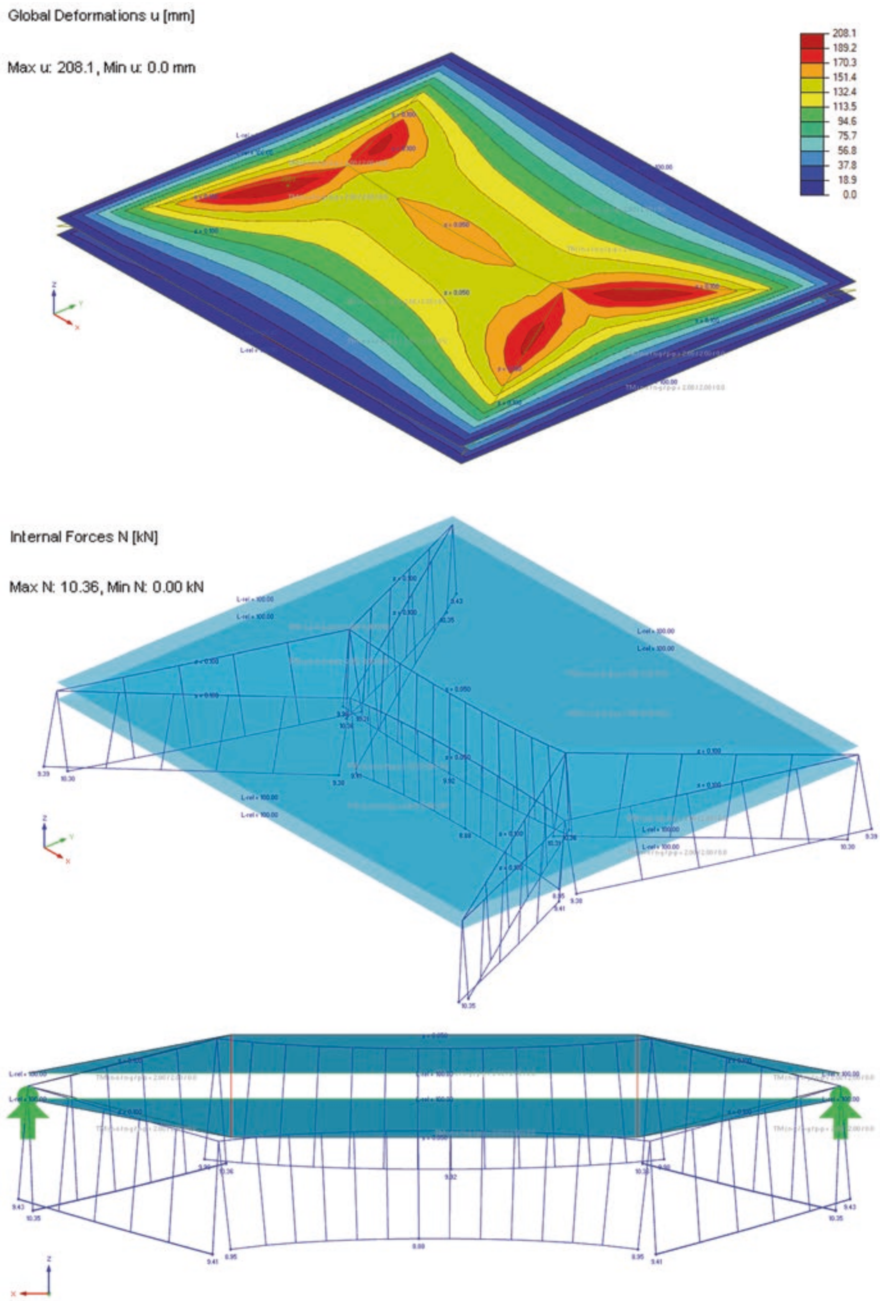

Fig. 10.11 Form-finding of the single-module tensegrity concept, with double membrane layers (cyan surfaces) that are tensioned by two flying masts (red lines). From top to bottom: plots of global deformations *U* [mm] and Internal forces *N* [kN]

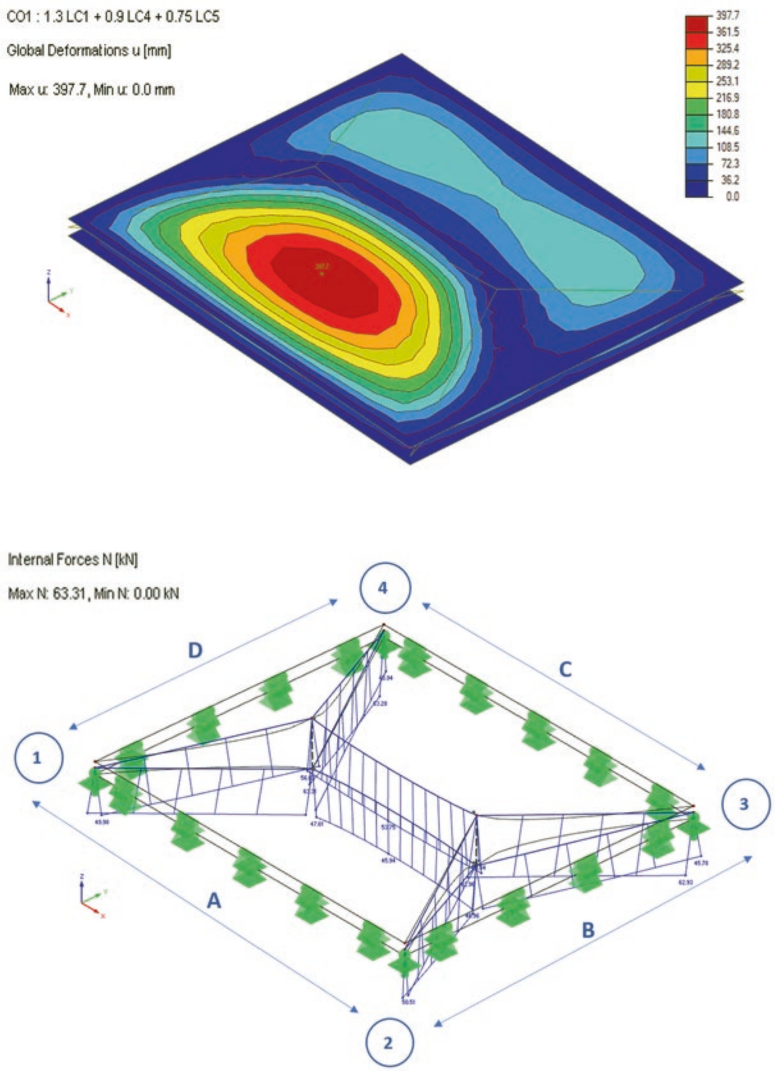

Fig. 10.12 *ULS = 1.3 Self-weight + 0.9 Wind-Load (−Y) + 0.75 Snow-Load*, applied to the single-module tensegrity concept. From top to bottom: plots of global deformations *U* [mm] and Internal forces *N* [kN]

10.4.3 Membrane Compensation and Cutting Pattern

In addition to the form-finding process, the cutting pattern generation is inherently connected to the membrane structure design, where the goal is to divide the spatial shape into a set of patterns and to find their closest equivalent in the plane by the flattening. This is the consequence of the double curvature of membrane shapes that cannot be flattened without compromises, and thus, the curved patterns must be approximated by flat patterns.

10.4.4 Technological Design of the Anchoring System

The temporality of the function and the lightness of the construction system are compatible and almost necessarily linked requirements unless to consider a large use of equipment during the transport and installation phases; the process proposed by the designers is instead more difficult and unusual because they wanted to combine temporality and lightness with a planned re-use introducing in a temporary building typical issues of maintenance through time that can arise from the repetitiveness of the assembly and disassembly activities of an articulated set of components.

Considering the requirement to cover the exact perimeter of the atrium with a pitched geometry, the tensile surface will be anchored using rigid connections. Rigid edges are boundaries where the fabric is held continuously by a supporting structure having much greater lateral stiffness compared with that of the fabric. They are collected by bending resistant structural elements that works as clamped edges. These elements are designed as thin as possible, to avoid struggles against the lightness of the membrane (Fig. 10.13).

In case of double-layer roof, for each side of the atrium, the upper and the bottom membrane layers are clamped separately in two diverse keder rails by means of a thin, trapezoidal steel profile placed on the top of the structural steel square beams (Fig. 10.14).

The adoption of two keders per each edge – and not a single that join both membranes – avoids thermal bridges and makes easier the maintenance and the replacement of the elements. The typical keder cross section of the metal rails permits to fill up the galvanized steel cables that are contained into the textile pockets, realized on the edges of the membrane layers during the welding process. The steel

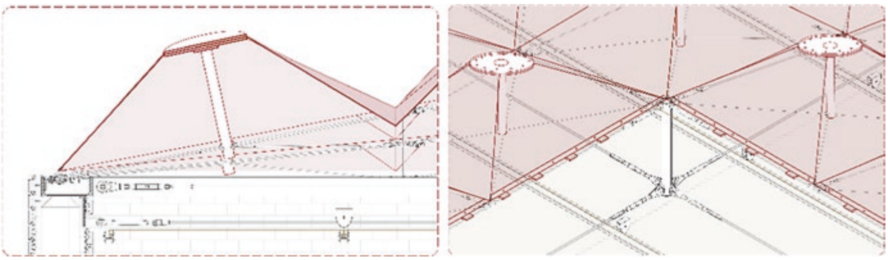

Fig. 10.13 Multiple-module tensegrity concept: detail on the anchoring system of cables

Fig. 10.14 Single-module tensegrity concept: detail on the anchoring system of cables

rails, which are pre-assembled with the textile on-site, permit to lift both assembled frames (the upper and the bottom ones) and, consequently, to join them up the structural beams.

The sections of keder bars are galvanized steel products, and the clamping details include strips made from elastomeric materials laid between the membranes and the clamping sections to protect the fabric against all mechanical, chemical and thermal actions. Such elastomers are integrated directly into clamping elements in the form of factory-fitted polymer edge beads (Knippers et al. 2011).

Using the keder system, forces travel perpendicularly into the steel ropes on the edges of the roof; movements along the cables must be prevented, and the angle for the pocket has to be chosen to be small enough to limit peeling forces in the seam. In order to ensure that the keder does not deform under load to such an extent that it slips out of its rail, it should exhibit a shore hardness of at least SH 50.

10.5 Conclusion

A systematic examination of the key aspects for the replicability of the method presented here through the two case studies is still in progress. The multidisciplinary researcher-based intervention method seems to be applicable in various scenarios of protection of the architectural heritage, with specific reference to the usability of museum spaces and the role reserved for technological and environmental planning in future transformative processes. The precautional principle in adopting a new shape and building system, the simulation designing tools and their validation by real samples measurements are the necessary steps for any innovative design path applicable to our common cultural heritage assets. They are not enough: a longer testing campaign along the service life of the ancient building and the final possibility to dismantle the additional protective structure easily are crucial for avoiding future permanent damages due to a lack of knowledge or lack of experienced use of any new material.

In conclusion, it can be stated that the application of ultra-light construction systems for the enhancement and conservation of heritage has the undeniable advantage of touching existing structures lightly and reversibly, loading them at least 10 times less than traditional construction techniques. Another advantage is represented by the shortening of the process from design to installation and by the guarantee that the reduced number of operators involved ensures a higher quality of the result. The current limit, also highlighted by the case studies presented, is that the best performing materials are still to be more and more tested and validated, also thanks to the multidisciplinary study methodology that has been proposed here. The awareness of researchers must be appropriately supported by the willingness of administrators to prefer solutions that might be evaluated in a multidisciplinary and comparative way rather than to adopt simplified and immediately available solutions, aiming at the preservation of assets in the longer term for future generations.

Acknowledgements The authors would like to thank the producers of the first case study's tested materials (4Spaces © and Trevira CS) for providing the material. The lab-scale prototypes and all the mechanical tensile tests were performed at Textiles HUB, the Interdepartmental research laboratory on textiles and polymeric materials at Politecnico di Milano.

References

4Spaces© All Products. Switzerland: 4Spaces© textile label (2017) Collection: Ogliastra, Levanzo. Available from: https://www.4spaces.ch/collections/collection-a. Accessed Oct 2017

Bletzinger K, Ramm E (1999) A general finite element approach to the form finding of tensile structures by the updated reference strategy. Int J Space Struct 14(2):131–145

Ahlquist S, Lienhard J, Knippers J, Menges A (2013) Exploring material reciprocities for textile-hybrid systems as spatial structures. In: Stacey M (ed) Prototyping architecture: the conference papers, 1st edn. Riverside Architectural Press, Cambridge, pp 187–210

Cremers J (2009) Designing the light-new textile architecture. In: Knaack U, Klein T (eds) The future envelope 3-facades-the making of, proceedings. TU Delft, pp 81–91

Demas M (2013) Protective shelters for archaeological sites. In: Roby T, Demas M (eds) Mosaics in situ. An overview of the literature on conservation of mosaics in situ. J. Paul Getty Trust, Los Angeles. (Chapter 4). Available at: http://www.getty.edu/conservation/publications_resources/pdf_publications/pdf/lit_review.pdf. Accessed: July 2023

Forster B, Mollaert M (2004) European design guide for tensile surface structures. Vrije Univ. Brussel, Brussel

Huang ZM, Ramakrishna S, Tay AA (2000) Modeling the stress/strain behavior of a knitted fabric-reinforced elastomer composite. Compos Sci Technol 60(5):671–691

Knippers J, Cremers J, Gabler M, Lienhard J (2011) Construction manual for polymers + membranes. https://doi.org/10.11129/detail.9783034614702

Kolo E (2018) New meets old: textile hybrid architecture in the historical context of Castello Sforzesco in Milan. Master thesis, Politecnico di Milano, School of Architecture, Urban Studies and Costruction Enginnering. http://hdl.handle.net/10589/140681

Lienhard J (2014) Bending-active structures: form-finding strategies using elastic deformation in static and kinetic systems and the structural potentials therein. PhD thesis, ITKE, University of Stuttgart. [online]: https://elib.uni-stuttgart.de/handle/11682/124

Lienhard J, Bletzinger K (2010) "Tracing" the equilibrium – recent advances in numerical form finding. Int J Space Struct 25(2):107–116

Monticelli C, Zanelli A Kutlu A (2022) Design-driven uniaxial and biaxial tensile testing of knitted fabrics applied to construction. In: Proceedings of IBSE symposium, 25–27 May 2022, Prague, Czech Republic. ISBN 9781713853220

Rosina E, Zanelli A, Beccarelli P, Gargano M, Romoli E (2011) New procedures and materials for improving protection of archaealogical areas. In: Materials evaluation, Aug 2011, 979–989

Tamke M, Baranovskaya Y, Deleuran A, Monteiro F, Fangueiro R, Stranghöhner N, Uhlemann J, Schmeck M, Gengnagel C. (2016) Thomsen M. Bespoke materials for bespoke textile architecture. In: Proceedings of the International Association for Shell and Spatial structures (IASS) Tokyo symposium. Tokyo, Japan

Trevira® (2023) Flame retardant textiles – Trevira CS [Internet]. Germany: Trevira® yarn label; Available from: http://www.trevira.com/en/textiles-made-from-trevira/home-textiles/flame-retardant-textiles-trevira-cs.html. Accessed 31 July 2023

UNESCO, ICCROM, ICOMOS, IUCN (2013) Managing cultural world heritage. United Nations Educational, Scientific and Cultural Organization Publisher, Paris. Available from: http://whc.unesco.org/en/activities/827/. Accessed 10 July 2023

Zanelli A (2009) Fire resistant textiles/Tessili resistenti al fuoco. In: Arketipo, n.39/09, 104–112, ISSN1828-4450

Zanelli A (2015) Architectural fabric structure in the refurbishment of archaeological and cultural heritage areas. In: Llorens JI (ed) Fabric structures in architecture. Woodhead Publishing, Elsevier, pp 481–527. https://doi.org/10.1016/B978-1-78242-233-4.00015-2

Zanelli A, Kolo E, Monticelli C, Rosina E, Poli T, Speroni A, Mainini AG, Cardena JDB (2020) A removable textile hybrid structural screen for the windows of Castello Sforzesco, Milan: when experimental metrics inform the bespoke ‘design-to-construction’ process in historical contexts. Archit Eng Des Manag TAEM20:1–21., ISSN: 1752-7589. https://doi.org/10.1080/17452007.2020.1783506

Zanelli A, Monticelli C, Jakica N, Fan Z (2023) Lightweight energy. Membrane architecture exploiting natural renewable resources. Springer Nature. https://doi.org/10.1007/978-3-031-08154-5

Index

A. Battisti, S. Baiani (eds.), *ETHICS: Endorse Technologies for Heritage Innovation*, Designing Environments,
https://doi.org/10.1007/978-3-031-50121-0